

The Final Report

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Woven Fabrics**

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Permeability Prediction of Three-
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Report

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Abstract

Liquid molding processes are becoming more popular among the composite manufacturing industries due to their versatility and economy among other merits. In analyzing the flow during the process, permeability is the most important parameter. Permeability has been regarded as a property of the porous medium. However, in many practical cases, the value may vary depending on the flow conditions such as the flow rate. It is speculated that this deviation is caused by inhomogeneous microstructure of the medium. In this study, numerical simulations as well as experimental measurements have been done to investigate the cause of deviation. Microstructure of porous medium was modeled as an array of porous cylinders. Resin flow through the array was simulated numerically. Simulations were performed for two different flow conditions, namely saturated flow and unsaturated flow. Based upon the results, permeabilities were estimated and compared for the two flow conditions. In addition, a model was proposed to predict the permeability for different flow conditions. Results showed that experimental data were in agreement with the prediction by the model.

Introduction

Liquid composite molding processes are widely used for manufacturing fiber reinforced polymer composites. These processes offer advantages of low cost and high quality and versatility(Fig. 1).

In case of liquid composite molding, understanding of the resin flow in a porous preform is very important[1]. To characterize the flow through a porous medium, using permeability is a conventional way. Permeability is defined by Darcy's law which can be written as the following equation[2].

$$\frac{Q}{A} = -\frac{\mathbf{K}}{\mu} \nabla p \quad (1)$$

where Q is the volumetric flow rate, A is the normal cross-sectional area, ∇p is the pressure gradient and μ is the viscosity of the resin. \mathbf{K} represents the permeability tensor of the medium.

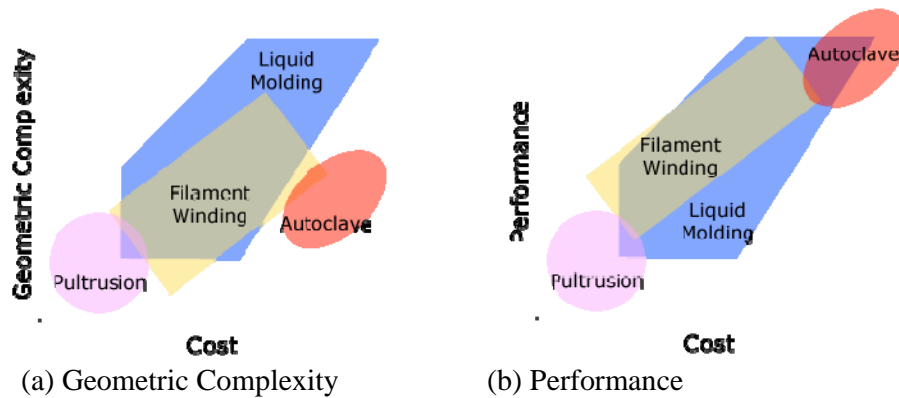


Figure 1 The tradeoff between cost and some factors provided by various processes[1]

Permeability has been regarded as a value which is not affected by the flow conditions such as the viscosity of the fluid. However, in many practical cases, the value may vary depending on the flow situations[1,3]. In this study, numerical simulations were done to investigate the causes and tendency of the deviation in permeability.

Numerical Analysis

Problem Statement

The permeability of the preform may be estimated by several methods and some correlations are available[2,4,5]. In practice, the microstructure of fiber preforms is usually not homogeneous, and the permeability used so far may be invalid in unsaturated flow. In this work, microstructure of porous medium was modeled as an array of porous cylinders. Many fiber preforms are made up of fiber tows(Fig. 2). A fiber tow consists of hundreds of fiber filaments whose diameter is about 20~30 μm and the gap size between the filaments is on the order of μm so that the fiber tow can be regarded as a homogeneous porous media. In contrast, dimension of the channel between tows is on the order of mm . The analysis of the unsaturated resin flow becomes a multi-phase problem. One is Stokes' flow in channels described by the Navier-Stokes equations and the other is porous media flow within tows, which is governed by Darcy's law.

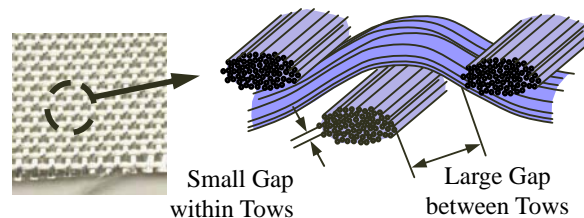


Figure 2 Microstructure of a typical woven fiber preform

The governing equations for the channel flow are the continuity and the momentum equations:

$$\text{Continuity : } \nabla \cdot \vec{v} = 0 \quad (2)$$

$$\text{Momentum : } \rho \left[\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} \right] = -\nabla p + \mu \nabla^2 \vec{v} + \mathbf{f} \quad (3)$$

where \vec{v} is the flow velocity, ρ is the fluid density, μ is the resin viscosity and \mathbf{f} is the surface tension term for CSF(Continuum Surface Force) model used in this study[4] and it is described by following equation.

$$\mathbf{f} = \frac{\sigma}{[f]} \kappa \nabla f \quad (4)$$

where, σ is the surface tension coefficient, κ is the curvature of the interface and f is the fill fraction.

Inside the tows, flow follows the Darcy's law and capillary pressure need to be added to the pressure term therefore, Eq. 1 may modified as following Eq. 5.

$$\langle \vec{v} \rangle = \frac{\delta Q}{\delta A} = -\frac{\mathbf{K}}{\mu} \nabla (p + p^c) \quad (5)$$

where, $\langle \vec{v} \rangle$ is the Darcy velocity and p^c is the capillary pressure given by Young-Laplace relation in Eq. 6.

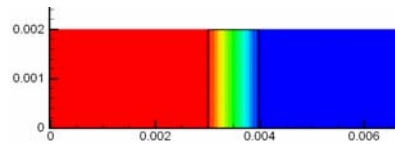
$$p^c = \frac{4\sigma \cos \psi}{D_E} \quad (6)$$

where, D_E is the equivalent wetted diameter of a fiber tow and ψ is the contact angle [6].

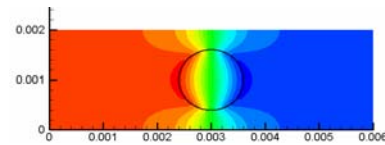
Numerical Results

Numerical simulations of the fluid flows were performed. In the simulation, VOF(Volume of Fluid)-based algorithm with fixed grid system was employed.

Steady state flows through a channel with a porous cylinder placed in the middle were solved for verification. There is a line inlet with the injection velocity of 3 /s from the left side(Fig. 3). First, a rectangular porous medium with permeability of 1.0×10^{11} and length of 1 is placed in the middle of the open space(Fig. 3a). The viscosity was 1.0 s and the pressure difference between left and right end of the porous media was 3×10^5 . Numerical result showed good agreement with the analytical solution by the Darcy's law. A case of circular shaped porous medium in open space was also



(a) Rectangular Porous Medium



(b) Circular Porous Medium

Figure 3 Steady State Pressure Distribution

considered(Fig. 3b). The result showed reasonable pressure distribution and it agreed with other reference data as well[7]. For unsaturated flow simulations, fiber tows were regarded as one dimensional array of porous cylinders(i.e. unidirectional fiber preform). Calculated pressure profile and fill fraction are illustrated in Fig. 4a and Fig. 4b, respectively. The tow permeability used for calculation was 0.5×10^{-10} and the inlet velocity was 3 /s. In the saturated region, the pressure profile was linear and the permeability estimated by the pressure gradient and flow velocity was identical to the saturated permeability of this preform. However, there was sudden pressure drop at the beginning of unsaturated region and this pressure drop may cause the difference of unsaturated and saturated permeability. In unsaturated region, to obtain the permeability for Darcy's law, the Darcy velocity should be used. Using the Darcy velocity, the practical flow front was pointed with vertical arrows. As can be seen in the Fig. 4a, the

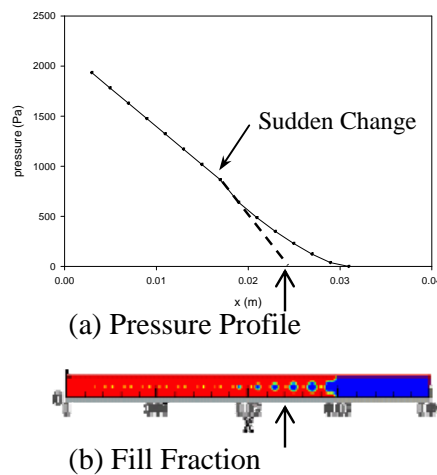


Figure 4 Unsaturation Flow Simulation

slope of pressure curve in unsaturated region was stiffer than that of saturated region which means that unsaturated permeability was smaller. By the calculation, the values of saturated and unsaturated permeability was 1.4×10^{-9} and 0.91×10^{-9} . The permeability was 34.4% reduced due to poor saturation. In addition, the range of unsaturated region was investigated. Fig. 5 shows that the length of the region remains constant.

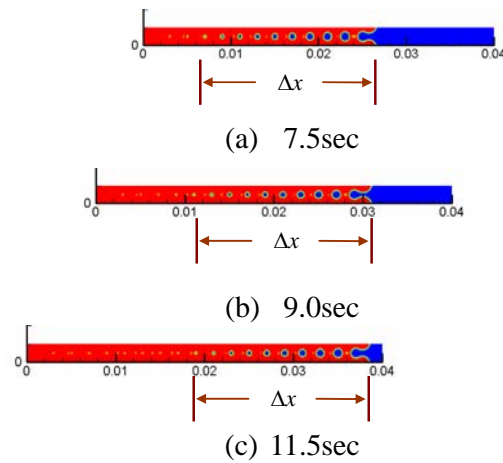


Figure 5 Length of Unsaturated Region

Experiments

Experiments to investigate saturated and unsaturated permeability were performed. The setup is illustrated in Fig. 6. Ten pressure sensors were installed along the flow direction and line inlet was located at the left end so that the flow was one dimensional.

In experiments, two flow directions were investigated. One is the fiber direction and the other is the cross direction(perpendicular to fiber direction). The pressure gradient and pressure profiles are shown in Fig. 7.

The ratio of pressure gradients in saturated and unsaturated region stands for the

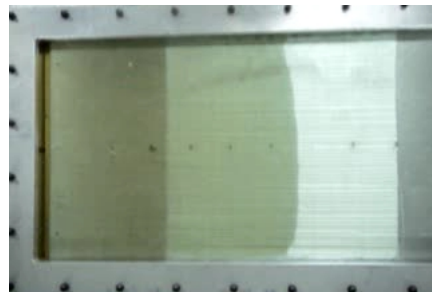
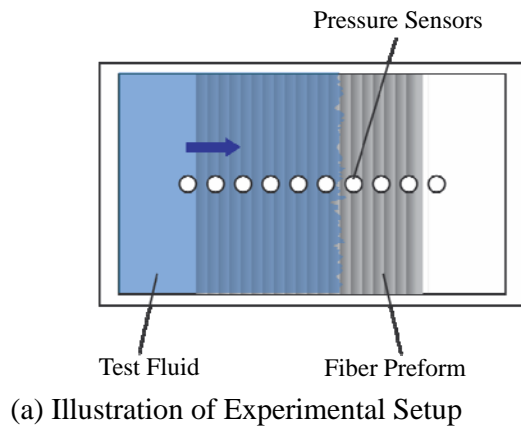
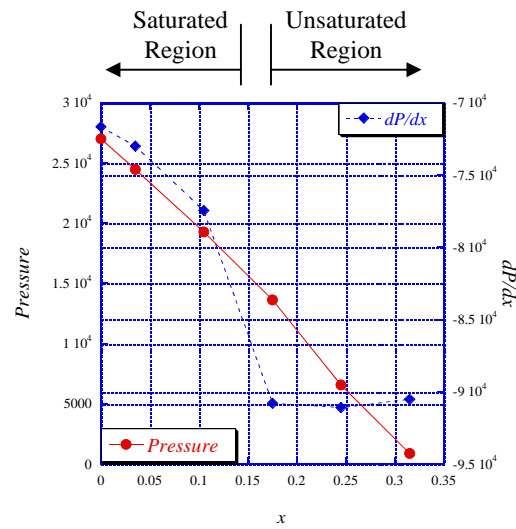
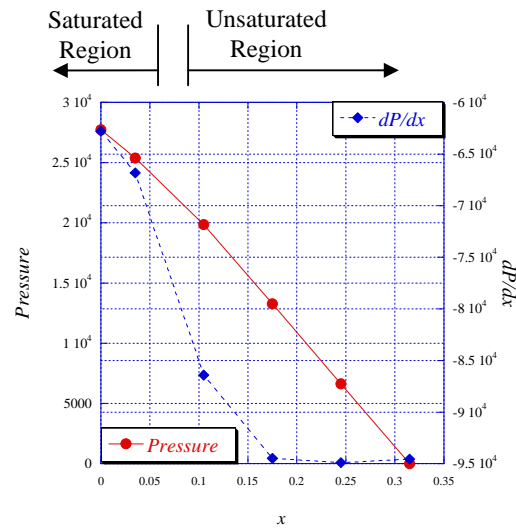


Figure 6 Experimental Setup

permeability ratio. In these experiments, permeability ratios are 0.7892 and 0.6635 for fiber direction and cross direction, respectively. These results agree with the data obtained from the numerical simulations.



(a) Fiber Direction



(b) Cross Direction

Figure 7 Experimental Results: Pressure Profiles and Pressure Gradients

Conclusions

A numerical simulation code was developed to investigate the saturated and unsaturated permeabilities. In this simulation there were two calculation domains. One was for the porous flow in tows and the other was for Stokes' flow in channels. From the simulations, it was shown that microstructure of fiber preform affects the flow and permeability. In addition, experiments for unidirectional fiber preform were performed and the result showed the same tendency as the simulations.

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